Predicting Soil Erosion for Alternative Land Uses

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ABSTRACT

The APEX (Agricultural Policy–Environmental eXtender) model developed in the United States was calibrated for northwestern China's conditions. The model was then used to investigate soil erosion effects associated with alternative land uses at the ZFG (Zi-Fang-Gully) watershed in northwestern China. The results indicated that the APEX model could be calibrated reasonably well (±15% errors) to fit those areas with >50% slope within the watershed. Factors being considered during calibration include runoff, RUSLE (Revised Universal Soil Loss Equation) slope length and steepness factor, channel capacity flow rate, floodplain saturated hydraulic conductivity, and RUSLE C factor coefficient. No changes were made in the APEX computer code. Predictions suggest that reforestation is the best practice among the eight alternative land uses (the status quo, all grass, all grain, all grazing, all forest, half tree and half grass, 70% tree and 30% grain, and construction of a reservoir) for control of water runoff and soil erosion. Construction of a reservoir is the most effective strategy for controlling sediment yield although it does nothing to control upland erosion. For every 1 Mg of crop yield, 11 Mg of soil were lost during the 30-yr simulation period, suggesting that expanding land use for food production should not be encouraged on the ZFG watershed. Grass species are less effective than trees in controlling runoff and erosion on steep slopes because trees generally have deeper and more stable root systems.

THE LOESS PLATEAU (LP) in northwest China has a total land area of 627 000 km^2. Wind-deposited loess soils in the middle reaches of the Yellow River of China are among the most erodible soils in the world. About 50% of this land area has soil losses that average 40–50 Mg ha^{-1} yr^{-1} and may be as high as 100 to 200 Mg ha^{-1} yr^{-1} (Gao et al., 2002; Huang et al., 2003; Zhang, 2002). The water and soil eroded land area on the LP accounts for three-fifths of the total soil eroded land area in China. In the last four decades, average soil loss ranged from 20 to 250 Mg km^{-2} yr^{-1}, which translates to 2.0 to 20 mm yr^{-1} of soil depth. The annual total sediment load of the Yellow River is 1600 million Mg, with about 90% of the sediment originating from the LP. About 400 million Mg of soil were transported to the Yellow River, causing an increase of 80 to 100 mm yr^{-1} in the riverbed (Deng and Yuan, 2001).

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Along with the soil loss, significant amounts of nutrients are lost from the cropland soils, depleting the soil fertility of the LP area. There are 6.4 million Mg of organic matter, 416 000 Mg of N, 2.10 million Mg of P, and 33.76 million Mg of K being transported annually to the Yellow River (Zhao et al., 2002). This massive soil nutrient loss lowers cropland productivity. The annual grain yield including corn (*Zea mays* L.), pearl millet [*Pennisetum glaucum* (L.) R. Br.], and sorghum (*Sorghum bicolor* L.) averaged only 416 kg ha^{-1} yr^{-1} in the LP area (Ansai Statistical Bureau, 2003, p. 10–15).

Research on soil erosion, particularly in the LP area, has focused on identifying the significant effects of soil erosion, assessing damage, and identifying farming practices and other factors that control soil erosion (Chen et al., 2002; Cheng, 2002; Wang et al., 2002a). While many of these factors contributed to the soil loss in this region, high-intensity summer rainstorms, steep slopes, erosive loess soils, and land development also contribute to this severe erosion problem. Inappropriate land use practices such as deforestation, overgrazing, intensive crop production, mining, and construction projects aggravate the soil loss from this region (Liang et al., 2003; Sun et al., 2003).

Converting grassland into cropland, beginning in the 1950s and continuing into the 1990s, has intensified soil erosion severity in the LP (Hao and Dang, 2003; Peng et al., 2002; Wei and Zhu, 2002). In most cases, the adverse effects of soil erosion on cropland are more severe than on grassland. Thus, the current priority for soil erosion control should be that of converting cropland back to grasslands and forests (Dong and Chen, 1997).

Adequate soil erosion control requires a quantitative understanding of the mechanisms governing soil erosion, identifying those major factors that cause soil erosion, predicting the amount and distribution of soil loss in relation to possible causal factors, and making an erosion assessment for alternative best management practices that can be used to facilitate conservation policies (Castillo et al., 1997; Dabney et al., 1995; Gao et al., 2002).

Conceptual watershed models have been developed to assess the effects of changes in land use, land cover, management practices, or climactic conditions on water and soil erosion at both small and large watershed scales. Examples of continuous watershed simulation models reported in the literature include CREAMS (a field-scale model for Chemicals, Runoff, and Erosion from Agricultural Management Systems; Knisel, 1980), ALMANAC (Agricultural Land Management Alternatives with Numerical Assessment Criteria; Kiniry et al.,

Abbreviations: APEX, Agricultural Policy–Environmental eXtender; LP, Loess Plateau; RUSLE, Revised Universal Soil Loss Equation; ZFG, Zi-Fang-Gully.

1992), APEX (Williams and Izaurralde, 2005), and SWAT (Soil and Water Assessment Tool; Arnold et al., 1998). These models generally use a daily time step, are computationally efficient, and often lump many detailed processes that occur in short time steps into simplified daily approximations.

The APEX model was developed for use in whole farm and small watershed management. The model was constructed to evaluate various land management practices considering sustainability, erosion (wind, sheet, and channel), economics, water supply and quality, soil quality, weather, and pests. Management capabilities include irrigation, drainage, furrow diking, crop rotations, fertilization, grazing, and tillage (Williams and Izaurralde, 2005).

The APEX model is a daily time-step crop simulation and environmental assessment model that simulates alternative crop systems and cultural practices and their environmental impacts. The model uses soil and climate data, cultural practices, cropping systems, and management data. More than 60 major crops, several minor crops and vegetables, and a few grasses and trees can be simulated with time in continuous single or multiple crop rotations.

The results include projected crop yields, runoff, percolation, water and wind erosion, and nutrient and pesticide uptake, storage, and losses for each subsection of the watershed as well as the total watershed. The APEX model has been used in the USA to evaluate government policy effects on soil erosion (Chen et al., 2000, Wang et al., 2002b) but has been used very little in China.

This study had two aspects. One was to calibrate the APEX model for an agricultural environmental study in northwestern China. The other was to use the calibrated APEX model to conduct a case study using the ZFG watershed in Ansai County of Shaanxi Province in northwestern China to demonstrate how the model can be effectively used for soil erosion management. Specifically, the latter part of the study evaluated soil erosion impacts under alternative land management strategies such as reservoir construction, grain production, livestock grazing, revegetation, and reforestation.

BACKGROUND

Agricultural simulation models were developed in the early 1980s and have been widely applied to agricultural environmental studies in the USA. One version of this series of simulation models is APEX. While both Chinese government officials and scientists are interested in adopting this USA-based agricultural model for their environmental studies and believe it is worthwhile for China to adopt this technology, there are legitimate concerns related to the applicability of this model to China's conditions. One concern is the utility of model assumptions for water runoff and soil loss estimations because they are based on U.S. conditions, which are quite different from China's. For example, in the USA, there is almost no cropland with slopes >15%, while in northwestern China slopes exceeding 50% are commonly planted to various kinds of crops. A demonstration study is needed to evaluate the suitability of the APEX methodology.

The study area selected for analysis was the ZFG watershed of Ansai County (36°51′30″ N lat; 109°19′30″ E long) in Shaanxi Province, northwestern China (Fig. 1). The ZFG watershed is classified in the loess ravine hilly land zone, which is well known for its chain of undulating hills, deep gullies, thick Yellow Earth soils (Xerertic Haplocambids), and high elevation (1100 m above sea level). Based on land cover, the zone is ascribed to a forest–grassland area. This watershed covers 8.27 km^2 with a ravine length of 8.06 km. The watershed has suffered from severe soil erosion in the last five decades, with an annual soil loss of 140 Mg ha^{-1} yr^{-1}. The climatic conditions are extreme. Annual precipitation reaches 550 mm, primarily received in July–September and annual potential evaporation is about 1400 mm. Yearly rainfall amount varies between 300 and 700 mm. Sunshine is intense at 2415 h yr^{-1}, accumulated annual temperature ($\geq$0°C) is 3733.5°C. Yellow Earth is the dominant soil, with an average soil depth >20 m. Yellow Earth soil (loess) is a material deposited by wind. The material is high in silt, with variable amounts of clay but <5% sand. Yellow Earth soils are generally fertile, fairly permeable with a very high available water-holding capacity (He et al., 2002). They can be very erosive when wet. Specifically, the Yellow Earth soil in the ZFG watershed is comprised of 10% sand, 68% silt, and 22% clay and it has 0.22 m^3 m^{-3} of field water-holding capacity, 0.036 m^3 m^{-3} of water content at the wilting point, and 0.18 m^3 m^{-3} of plant-available soil water, which is defined as the difference between field capacity and wilting point.

The ZFG watershed is the hinterland of the LP and is located in a transition zone from southeastern forest to northeastern grassland in northwestern China. Typical of the majority of LP land areas, ZFG once had dense forest and grassland cover and was commonly considered a crisscross area of agriculture and grassland animal husbandry. Since the Ming and Qing Dynasties (1368–1911), however, accompanied by national defense needs, population migration to northwest China

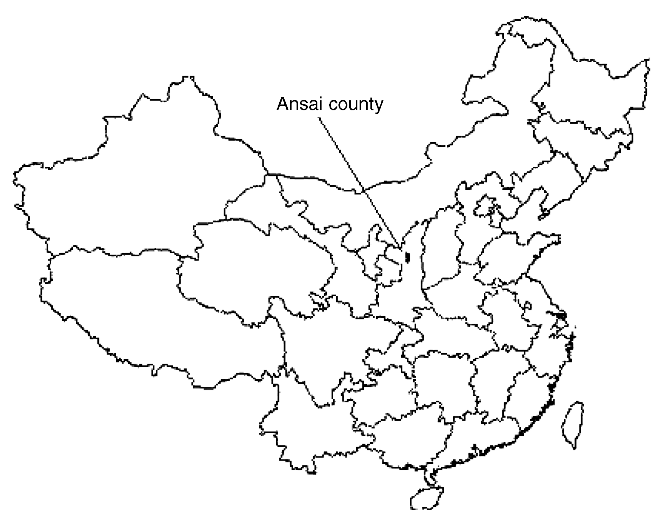

Fig. 1. Location of the Zi-Fang-Gully watershed in Ansai County, Shaanxi Province, People's Republic of China.

and conversion to intensive agriculture have taken place. Agricultural and livestock production as well as deforestation were rapidly expanded in the area and gradually removed the natural land cover, resulting in serious water-induced soil erosion. With the loss of topsoil, soil fertility deteriorated dramatically, contributing to lower grain yields. Farmers had to expand their cultivated hill land area for crop production to maintain the food supply, thus causing additional soil loss. This cycle evolved with time and was not changed until the early 1990s when the region began to enforce the HCRS (Household Contract Responsibility System). The purpose of the HCRS was to change the land use of the hilly and gully areas from grain and livestock production to grassland and forest. This was accomplished by allocating the land to farmers as an incentive to change land use. As the HCRS has been implemented, a series of soil conservation practices have been implemented at ZFG. These practices include the establishment of tree plantations and grass areas, construction of terraces, construction of control dams to reduce small gully erosion, construction of large flood-water retarding structures, reduction of grazing in woodland areas, and returning farmland to forest and grassland on highly sloping areas. However, restoring the previous land cover requires patience and the long-term effects remain to be seen.

MATERIALS AND METHODS

Locating and characterizing sub-areas by selected land uses within the ZFG watershed was the first step in applying the APEX model. Digital elevation measurements divided the watershed into 29 hydrologic sub-areas. The present land use of the watershed is 12% cropland, 50% grassland, and 38% woodland. Cropland location within each sub-area was determined from county and regional reports as well as local farm surveys (Ansai County agricultural statistical report, 2001, unpublished). Locations of the designated rangeland areas were developed from watershed observations based on the land use and land cover information.

Sub-area sizes, watershed hydraulic characteristics such as upland slope length and steepness, sub-area channel length and slope, and routing reach channel and floodplain length and slope were determined using digital elevation mapping combined with geographical information software and topographic maps. The ZFG watershed is covered uniformly with a Yellow Earth soil.

Climatic conditions were specified using historical weather records at the ZFG weather station. Annual average long-term simulated rainfall (Fig. 2) was 528 mm.

Environmental effects of soil erosion and nutrient losses associated with alternative land uses and management strategies were simulated using APEX.

Hydrology

Surface runoff is predicted for daily rainfall by using the Soil Conservation Service (SCS) curve number equation (USDA-SCS, 1972). The APEX model contains two methods for estimating peak runoff rate: the modified rational formula and the SCS TR-55 method (USDA-SCS, 1986). The rational method was used for this watershed simulation. Potential evapotranspiration (PET) was estimated using Hargreaves and Samani (1985) because wind speed, relative humidity, and solar radiation data were not available. Hargreaves' method

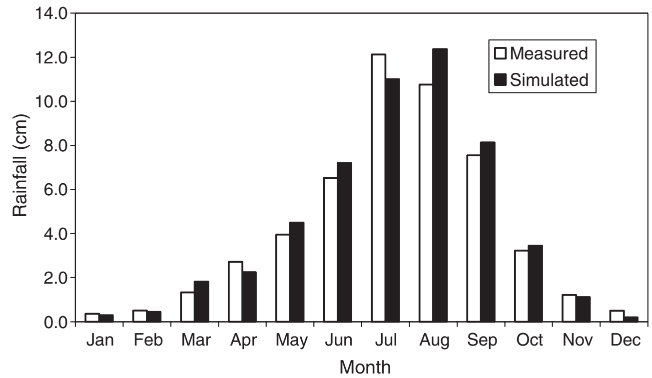

Fig. 2. Actual and simulated monthly average precipitation in the Zi-Fang-Gully watershed, Ansai, during 30 yr.

uses temperature and extraterrestrial radiation to estimate daily PET and gives realistic results in most cases (Williams and Izaurralde, 2005). The model computes evaporation from soils and plants separately, as described by Ritchie (1972). Potential soil water evaporation is estimated as a function of potential evaporation and leaf area index. Actual soil water evaporation is estimated by using exponential functions of soil depth and water content. Plant water evaporation is simulated as a linear function of potential evaporation and leaf area index.

Water-induced soil erosion was simulated with MUST (Williams and Izaurralde, 2005), a modified USLE (Wischmeier and Smith, 1978). Because the primary purpose of APEX is to simulate long-term water, sediment, nutrient, and pesticide yields from whole farms and small watersheds, traditional flood-routing methods are not used. Sediment is routed through the channel and floodplain separately. The sediment-routing equation is a variation of Bagnold's (1977) sediment transport equation. The new equation estimates the transport concentration capacity as a function of velocity.

The model was calibrated considering a small number of important parameters. The soil saturated conductivity was adjusted slightly to improve runoff volume estimates from the Green and Ampt infiltration equation. The floodplain saturated conductivity was set to 10^{-7} mm h^{-1} to eliminate floodplain infiltration. The SCS runoff curve number index coefficient was set to 2.5 (previous range was 0.5–2.0) to provide better initial abstraction values for the Green and Ampt equation. The RUSLE C factor coefficients relating crop residue and growing biomass to land cover were set to 1.0 (normal range is 0.5–1.5) and 0.5 (normal range is 0.3–1.0). Animal power and hand-hoe weed control operations were added to the tillage operation database. The mixing efficiency of the animal-drawn plow was set at 0.5 and the tillage depth at 75 mm. In general, soil compaction and tillage depth are less for animal and hand operations than for machinery operations.

Model Performance Evaluation

The APEX model was evaluated by comparing simulated crop yields, shrub yields, water runoff, and soil erosion against field measurements obtained from the ZFG watershed during 1997–2002. In this process, parameters associated with watershed hydrology, as described above, and crop growth were modified within realistic ranges. For example, potential heat units for corn, soybean, pearl millet, proso millet (*Panicum miliaceum* L. subsp. *miliaceum*), and potato (*Solanum tuberosum* L.) were set at 1700, 1500, 1400, 1400, and 1300 potential heat units and plant populations were set at 7, 25, 150, 150, and 5 plants m^{-2}, respectively.

Alternative Strategies to Reduce Soil Erosion

The calibrated APEX can be reliably used for environmental impact assessment associated with alternative land management practices and pertinent policy making. The primary purpose for conducting APEX simulations is to assist local policymakers in the ongoing policy debate related to land use within the ZFG watershed. One of the major challenges is to identify strategies that reconcile the inherent conflict between food production and soil protection in the area. The proposed alternatives reflect alternative land use practices. Obviously, APEX cannot answer all policy questions, but it may assist with defining: (i) the environmental effects of alternative land uses, (ii) soil–food tradeoffs, and (iii) best management practices.

The eight land use scenarios simulated include (i) the base, (ii) partial grazing, (iii) all grain production, (iv) all grass growth, (v) all forest planting, (vi) 50% forest and 50% grass, (vii) 95% forest and 5% crop where the land area with slope <5% was used for crop production, and (viii) all grain production with a reservoir controlling flow from 77% of the watershed (Table 1). The base consisted of current land cover and land use conditions in the ZFG watershed, which is 12% cropland, 50% grassland, and 38% woodland.

RESULTS AND DISCUSSION

Crop, Shrub, and Tree Yields

Long-term (30-yr) simulated crop yields were compared with observed yields (Table 2). Model inputs included land use, seeding rates, planting and harvesting dates, tillage type and dates, fertilizer rates and dates, cropland management, and weather. Table 2 shows the comparisons of simulated and observed crop, grass [little bluestem (*Schizachyrium* spp.), gramagrass (*Bouteloua* spp.), buffalograss (*Buchloë dactyloides* [Nutt.] Engelm.)], shrub [curly mesquite (*Hilaria belangerii*)], and tree [black locust (*Robinia pseudoacacia* L.)] yields, where crops were measured by grain yield and grasses, shrubs, and trees were measured by biomass yield. As indicated in Table 2, both simulated crop yields and biomass yields of shrubs and trees are very close to the observed data (<5% difference).

Table 1. The eight alternative land use scenarios used in the simulations.

Scenario	Land cover or use
Base	12% of cropland used for corn, sorghum, soybean, pearl millet, proso millet, and potato production; 50% grassland with bluestem, gramagrass, and buffalograss species; and 38% forest, primarily black locust.
Grazing	Same as the base except 50% grassland was used for grazing sheep or goats.
Grain	Crop production with a 5-yr crop rotation: corn–pearl millet–soybean–potato–proso millet.
Grass	Grassland with bluestem, gramagrass, and buffalograss species, with each accounting for one third.
Tree	Reforestation with black locust.
Tree and crop	95% black locust and 5% (land with slope <5%) in grain production.
Tree and grass	50% black locust and 50% grass.
Construction of reservoir	Building a reservoir in a sub-area in the watershed where water flow converges; land cover primarily bluestem, gramagrass, buffalograss, and black locust, etc.

Table 2. Comparison between actual and simulated average annual crop and shrub yields at the Zi-Fang-Gully watershed.

Name	Yield Observed	Yield Simulated
	Mg ha^{-1} yr^{-1}	
Corn (*Zea mays* L.)	5.26	5.24
Soybean [*Glycine max* (L.) Merr.]	1.14	1.13
Proso millet (*Panicum miliaceum* L.)	1.87	1.77
Potato (*Solanum tuberosum* L.)	2.54	2.53
Pearl millet [*Pennisetum glaucum* (L.) R. Br.]	2.86	2.88
Sorghum [*Sorghum bicolor* (L.) Moench]	3.97	4.19
Buckwheat (*Fagopyrum esculentum* Moench)	1.53	1.59
Little bluestem grass (*Andropogon* spp.)	1.55	1.54
Gramagrass (*Bouteloua* spp.)	1.00	1.00
Buffalograss [*Buchloë dactyloides* (Nutt.) Engelm.]	1.93	1.93
Black locust (*Robinia pseudoacacia* L.)	12.86	10.00
Mesquite (*Prosopis glandulosa* Torr.)	29.43	30.00

Water Runoff and Soil Erosion

The following results will reflect the performance of the calibrated APEX model. Simulated runoff and sediment yield were tested against the field-measured values (Table 3). The deviation of runoff magnitude, Dv, was calculated to account for the accumulation of differences between the observed and simulated values for the given period of analysis. The quantity Dv may be expressed as

$$\mathrm{Dv} = (V_{\mathrm{obs}} - V_{\mathrm{sim}})100/V_{\mathrm{obs}} \quad [1]$$

where Dv is the deviation of runoff or sediment, expressed as a percentage; V_{obs} is the total observed runoff or sediment for the simulated period; and V_{sim} is the total simulated runoff or sediment for the simulation period.

Table 3 shows that the simulated runoff and soil erosion compared closely with the observed values during 1997–2002. Both Dv for runoff and Dv for sediment are within ±15%. Close agreement between average annual observed and simulated runoff and sediment yield suggests that APEX can be useful in the LP of China. The 15% discrepancy between the observed and the simulated runoff values in 1997 may be partially attributed to lack of information about initial conditions and previous land use and management.

Runoff

Results for the alternative land use scenarios for the 30 years of simulated runoff are presented in Fig. 3. Runoff is presented in millimeters and rainfall in centimeters in Fig. 3 to scale the graph better. The highest runoff reached nearly 170 mm under grain production in Years 4 and 23.

The average annual runoff for the alternative scenarios is shown in Fig. 4. The reservoir scenario controlling flow from 77% of the watershed reduced the watershed water yield from 34 mm yr^{-1} in the base scenario to 15 mm yr^{-1}. The large water yield reduction was caused by evaporation and seepage losses from the reservoir. Less significant reductions in water yield resulted from the grass and tree scenarios, although the tree scenario reduced water yield to 26 mm yr^{-1}. The water yield reduction by trees is mainly caused by

Table 3. Annual observed and simulated runoff and sediment yield.

Year	Runoff			Soil erosion		
	Observed	Predicted	Error	Observed	Predicted	Error
	mm	mm	%	Mg ha^{-1}	Mg ha^{-1}	%
1997	5.5	4.7	15	0.9	1.0	−11.1
1998	9.1	9.7	−6.7	6.2	7.0	−13.3
1999	5.8	6.4	−10.3	16.4	15.4	6.2
2000	62.3	63.2	−1.5	66.9	61.8	7.6
2001	12.9	11.18	14.1	11.5	12.2	−6.1
2002	26.0	28.7	10.5	41.2	39.1	5.1
Avg.	20.3	21.8	−7.1	23.7	23.2	2.4

canopy interception and increased water use by the deep-rooted black locust tree. The largest water yield resulted from the grain production scenario (36 mm yr^{-1}), mainly because the relatively short growing season combined with tillage provided much less ground cover and evapotranspiration. The base and grazing scenarios generated very similar water yields because the land use was the same except there was no grazing in the base scenario. The tree-and-crop and all-tree scenarios also produced the same water yield, mainly because there is only 5% cropland in tree-and-crop and the crops are grown on land with <5% slope.

Analysis of daily precipitation data revealed that >70% (288.1 mm) of 409 mm of total rainfall in 2000 occurred in June–August. More than 44% (127 mm) was recorded in July. In contrast, only 158 mm (32.6% of the annual amount) occurred during June–August 2001. The APEX model was able to account for runoff variability due to these large differences in precipitation distribution mainly because of realistic evapotranspiration computations and the resulting soil water effect on runoff.

Of the eight management strategies, simulated reservoir construction and tree planting are predicted to be the most effective alternatives for runoff control in the ZFG watershed area.

Erosion and Sediment Yield

The highest sediment yield occurred in Years 4 and 23, as highly concentrated rainfall events took place in those 2 yr (Fig. 5). In Year 4, the grain scenario generated the highest level of sediment yield (330 Mg ha^{-1}), followed by base (250 Mg ha^{-1}), grazing (210 Mg ha^{-1}), tree and crop (149 Mg ha^{-1}), trees (45 Mg ha^{-1}), tree and grass (38 Mg ha^{-1}), grass (20 Mg ha^{-1}), and reservoir construction (17 Mg ha^{-1}). In Year 23, the grain scenario also created the highest sediment yield (175 Mg ha^{-1}), followed by base (160 Mg ha^{-1}), grazing (155 Mg ha^{-1}), tree and crop (158 Mg ha^{-1}), tree and grass (104 Mg ha^{-1}), grass (80 Mg ha^{-1}), trees (60 Mg ha^{-1}), and reservoir construction (35 Mg ha^{-1}). Besides these two extreme years, the simulated sediment yield was relatively constant, never exceeding 30 Mg ha^{-1}. As shown in Fig. 6, the reservoir scenario produced the lowest average annual sediment yield, followed by trees, grass, tree and crop, tree and grass, base, grazing, and grain. Sediment yield differed substantially among all the scenarios except for grass and tree-and-crop. The 7 Mg ha^{-1} produced by the reservoir scenario was 36% smaller than under the tree scenario (11 Mg ha^{-1}), which was 27% smaller than under the grass scenario (15 Mg ha^{-1}). Overall, the reservoir scenario generated a >50% lower sediment rate than most other scenarios in 25 yr out of 30. The tree-and-crop and grass scenarios generated very similar sediment yields but less than every other scenario except for the tree scenario (Fig. 6). This suggests that reforestation and grass conversion are the most effective methods for controlling upland erosion, while reservoir construction is the best method for reducing sediment yield.

Tradeoff between Soil Loss and Crop Yield

Crop production is costly, especially in areas with steep slopes. These costs can be attributed to several aspects including but not limited to loss of soil, nutrients, land cover, and biodiversity. It is possible to quantify the

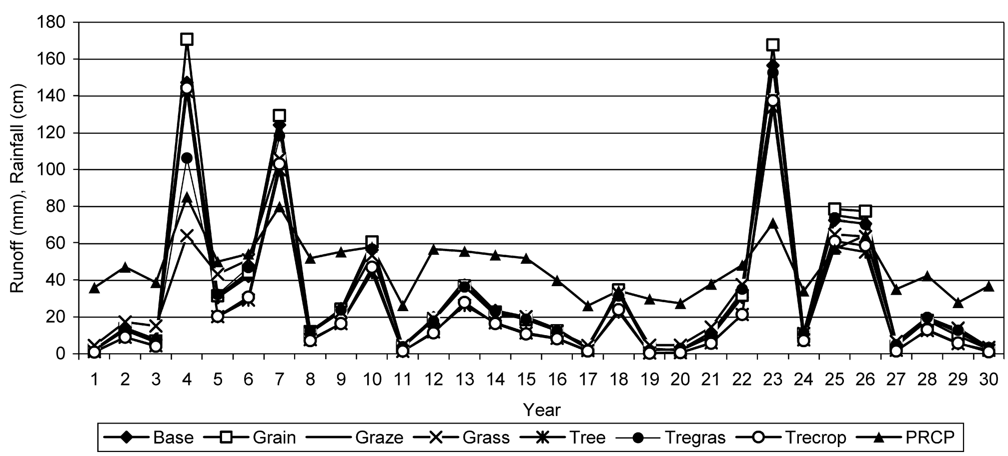

Fig. 3. Comparison of runoff between the alternative land uses.

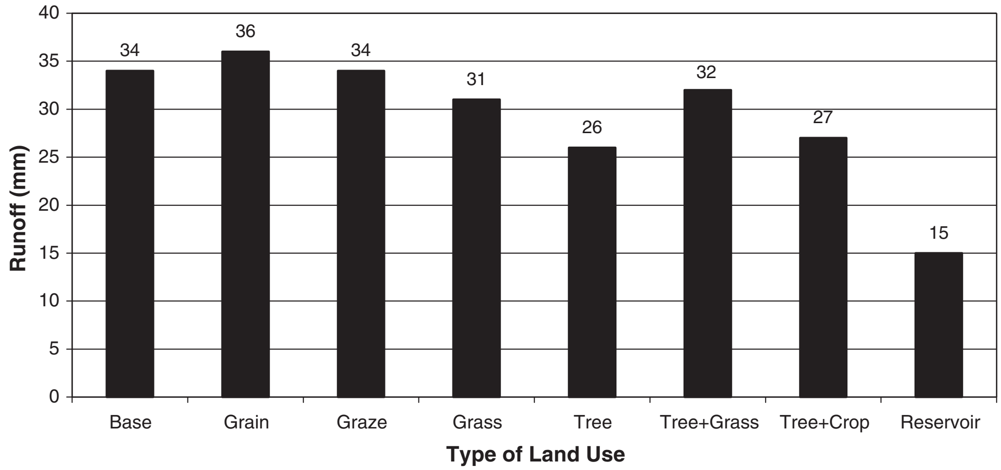

Fig. 4. Annual average runoff level of alternative land uses.

costs ascribed to each category. Doing so, however, is a very challenging task due to the limited data available in this area. Data such as biodiversity and evolution of vegetative species as well as production costs are very scarce for the ZFG watershed. Thus, our analysis was simplified by computing the tradeoff ratio between soil loss and crop yield only. Left out of the analysis were other land use products such as trees, fruits, bushes, and grasses, etc. Data for soil losses and selective crop yields can be acquired directly from the APEX simulation results. The quantity of soil loss and crop yield was lump-summed every 5 yr to be consistent with the 5-yr crop rotation period (corn–pearl millet–soybean–potato–proso millet). Thus, there are six aggregated soil loss and crop yield results.

Soil erosion for each 5-yr period (Fig. 7) was dominated by the annual precipitation pattern. In contrast, crop yield seemed to be stable at 3 Mg ha^{-1}. For instance, in both the first 5 yr and the third 5 yr, the annual crop yield averaged 3.0 Mg ha^{-1} but the sediment yield was significantly different between the two periods. The average annual sediment yield for the first 5 yr was 73 Mg ha^{-1}, compared with 8 Mg ha^{-1} during the third 5-yr period. These observations revealed that heavy and concentrated rainfall causes high runoff and consequently high soil erosion and sediment yield rates.

The information in Fig. 7 was used directly to compute the tradeoff ratio between sediment yield and crop yield for each 5 yr. Sediment yield/crop yield ratios varied substantially across each of the 5-yr periods (2.6–24.3; Fig. 8). On average, each 1 Mg of crop yield production on the entire watershed incurred 11 Mg of sediment yield during the 30-yr simulation period under the grain scenario. Thus, using the entire land area for crop production in ZFG is inconsistent with the goal of sustainable economic development. By contrast, the base scenario, with 12% of the land used for crop production, resulted in 8.7 Mg of sediment yield from 1 Mg of food production. The tree-and-crop scenario, however, seemed to have a better sediment/crop ratio than either total grain production or the base scenario. Each 1 Mg of crop production on those 41 ha of <5% slope under the tree-and-crop scenario incurred only 6 Mg of sediment yield. This suggests that it may still be feasible to use those gentle slope land areas for crop production. However, this may not be important as far as the general land use policy is considered due to the fact that the food production from areas with <5% slopes (41 ha) is far

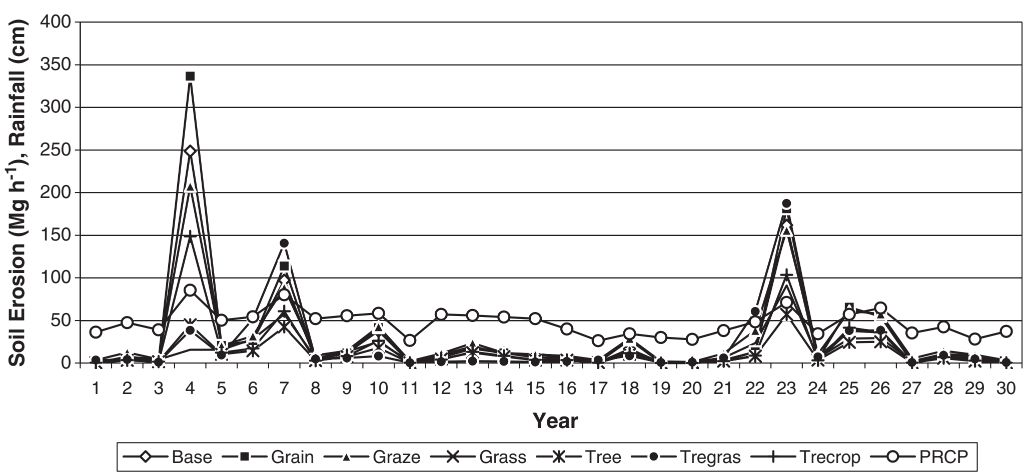

Fig. 5. Comparison of soil erosion between the alternative land uses.

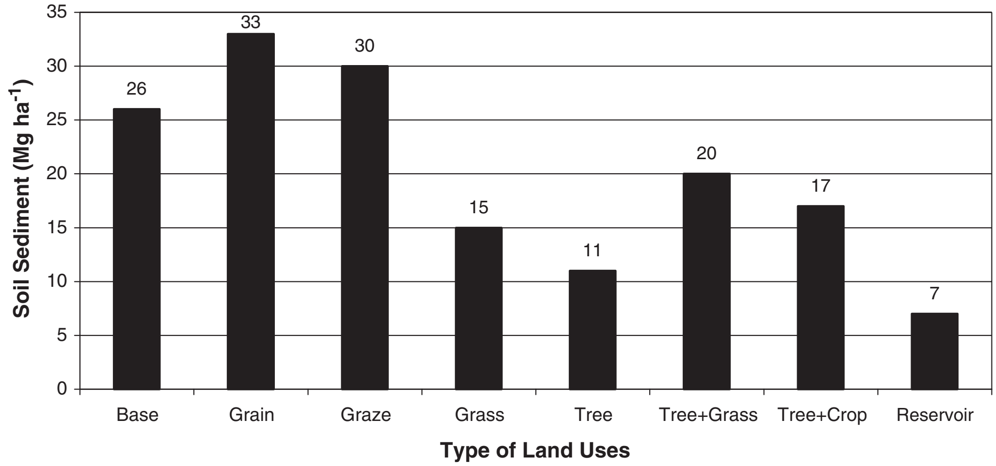

Fig. 6. Annual average soil sediment under alternative land uses.

from sufficient to meet food demand in the ZFG watershed area.

Social and Economic Implications of Elimination of Crop Production

A paradox exists in developing policies for soil loss control in the ZFG watershed area. Engineering measures such as reservoir construction require a significant investment and subsequent maintenance costs as well. Given the current economic conditions in the ZFG area, reservoir construction would be very difficult, if not impossible. Also, reservoirs do not control upland erosion although they are very effective in reducing sediment yield to major downstream reservoirs and rivers. Conversion of the majority of cropland into forests and grasslands is essential to reduce soil erosion and protect and preserve the Yellow River; although crop production can still be maintained on those small land areas with <5% slope, such practices reduce food production. Additionally, changing current land uses to grasses and trees alters a farmer's job opportunities. The traditional agrarian community has to learn how to manage orchards and trees or they need to change their traditional lifestyle by looking for new employment outside their village area. These changes may worsen local farmers' welfare in the short run because farmers living in remote areas are inclined to be less willing to alter their traditional lifestyle (Tefertiller, 2001). Government environmental policies and programs must consider the local farmers' welfare as well as soil conservation.

In addition, it is necessary to develop government policies and programs that provide incentives for applying soil erosion control practices through revegetation or reforestation. In this process, farmers who join the soil loss control program could be (i) hired for the restoration of forests and grasslands, (ii) compensated by a household income subsidy, or (iii) provided food through a government distribution program to compensate for food losses due to the elimination of grain and potato production.

SUMMARY AND CONCLUSIONS

The APEX model developed in the United States was validated to fit China's conditions. Then the model was used to investigate soil erosion effects associated with alternative land use scenarios in the ZFG watershed.

The results indicated that the APEX model could be calibrated to fit steep-slope watersheds in northwestern China. Major factors being considered in this calibrating process involved the RUSLE slope length and steepness factor, channel capacity flow rate, floodplain saturated hydraulic conductivity, the SCS runoff curve number index coefficient, and the RUSLE C factor coefficient. Additionally, the tillage operation database required minor modifications. For example, the USA-based tillage database does not include animal plow or hand hoe weed control, which are essential tillage operations in

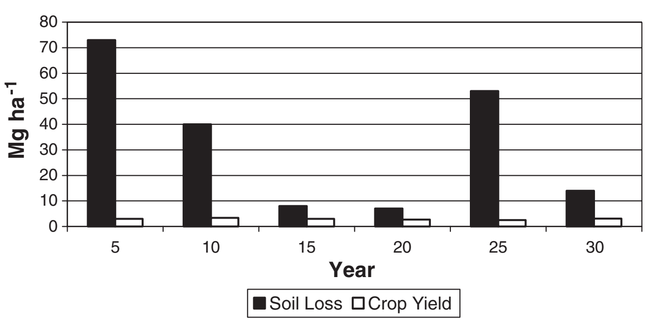

Fig. 7. Variations in soil loss and crop yield during the 30 yr of the simulation.

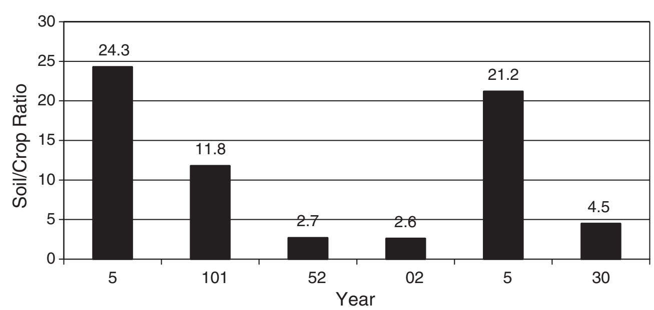

Fig. 8. Tradeoff ratios between soil loss and crop yield.

northwestern China. Minor changes to the APEX crop database included the harvest index and biomass/energy ratio for a few crops. Also, parameters or coefficients associated with the operation schedule, such as plant population, and potential heat units were set to reflect actual local conditions. No changes were made in the APEX computer code. These simulations suggest that the APEX model is useful for environmental studies not only in the ZFG watershed but also in the majority of watershed areas in northwestern China. This conclusion is based on the facts that the ZFG represents a typical watershed environment in northwestern China in terms of its climate, topography, soil type and quality, land use and land cover, geological characteristics, farming conditions, and even the way of life. The area relies on much fewer mechanized farming techniques than in the USA and in most other areas of China. Thus, the experience accumulated in the ZFG watershed study can be easily extended to other areas in China.

The simulation results indicated that construction of reservoirs and reforestation or revegetation play the most effective role in reducing water runoff and sediment yield. Construction of a reservoir resulted in 15 mm of average annual runoff, which is 56% lower than the base and grazing scenarios, 42% less than planting trees (26 mm), 44% lower than the tree-and-crop scenario, 52% less than the grass scenario, 53% lower than the tree-and-grass scenario, and 58% lower than the grain scenario. Construction of a reservoir was even more efficient in reducing sediment yield: the average annual 7 Mg ha^{-1} sediment yield is 36% less than the tree scenario, 53% less than the grass scenario, 59% less than the tree-and-crop scenario, 65% less than the tree-and-grass scenario, 73% less than the base scenario, 77% less than the grazing scenario, and 79% less than the grain scenario. More importantly, retaining crop production on the portion of the watershed with $<$5% slope (41 ha) simulated in the tree-and-crop scenario does not appear to cause any substantial runoff and soil erosion effects compared with the single grass or combined tree-and-grass scenarios. This may suggest that continuing crop production on those small gentle land slope areas may be acceptable as far as runoff and soil erosion is concerned. However, this really does not matter as far as the land use policy is concerned because those land areas are too small to provide sufficient food supply to meet food demand in the ZFG area. Overall, the construction of reservoirs and tree planting are the best practices among the eight land use alternatives for control of water runoff and sediment yield in the ZFG watershed. Reservoirs are expensive and do not control upland erosion, although they are very effective in reducing sediment yield to major downstream reservoirs and rivers.

The tradeoff-ratio analysis of soil loss and crop yield revealed that for each 1 Mg of crop yield, 11 Mg of soil was lost during the 30-yr simulation period for the base scenario. This ratio varied substantially from one year to another, largely due to rainfall variation. By contrast, the crop yield was relatively stable. This suggests that the current land use on the ZFG watershed with 12% (99 ha) crop production should not be encouraged. Furthermore, the complete grain production and livestock grazing alternatives are also not good land use practices because each of these brought about excessive water runoff and soil losses combined with low crop yields. Grass species are more shallow rooted than trees and hence are much less effective in suppressing water runoff and soil erosion on this steep-slope land.

Limitations

This study is limited by the scarcity of validation of shrub and grass species yields measured in the field. Black locust trees, gramagrass, buffalograss, and bluestem species were assumed to be the tree and grass cover for the entire watershed, although there were actually many varieties of trees, shrubs, and grass species. The simulation for the livestock grazing operation is limited to one stocking rate (1.2 animal unit ha^{-1}). The actual stocking rate probably varies around 1.2 and could affect soil erosion estimates through more or less grazing than simulated here.

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